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GAMMA-RAY SPECTRA OF THE PRODUCTS OF THERMAL-NEUTRON FISSION OF ^{235}U AT SELECTED TIMES AFTER FISSION

U.S. NAVAL RADIOLOGICAL DEFENSE LABORATORY

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SUMMARY OF RESEARCH REPORT

GAMMA-RAY SPECTRA OF THE PRODUCTS OF THERMAL-NEUTRON FISSION OF ^{235}U AT SELECTED TIMES AFTER FISSION

USNRDL-TR-68-144, dated 16 August 1968, by L. R. Bunney and D. Sam

PURPOSE

The gamma-ray spectra of fission products resulting from nuclear weapon detonations provide basic data required in the preparation of practical plans for nuclear warfare defense. This information is of considerable interest to the Office of Civil Defense and the military services, since it is fundamental input to fallout exposure and shielding calculations.

This report presents gamma-ray spectra of the unfractionated products of thermal-neutron fission of ^{235}U. The spectral information was sought to improve the basis of calculation of fallout exposure rates as a function of time after fission. While the thermal-neutron fission of ^{235}U does not precisely reproduce the radioactive composition of fallout, the products of this fission process have been used frequently as an approximation of the products of a nuclear explosion and are frequently the basis of comparison with products of other types of fission.

The gamma-ray spectra of the unfractionated products resulting from thermal-neutron fission of ^{235}U will be used as controlled experimental information for comparison with those spectra resulting from fractionated fission products.

OBJECTIVE

The overall objective is to measure experimentally the effects of fractionation of selected fission products on gross fission product gamma-ray spectra and to evaluate these effects on exposure rates calculated from these gamma-ray spectra. The first phase of this project is to conduct experimental measurements of the gamma-ray spectra of the unfractionated products of thermal-neutron fission of ^{235}U. The second phase of this project is to conduct experimental measurements of the gamma-ray spectra of the fractionated products of thermal-neutron fission of ^{235}U. This report covers the first phase of this project.

SCOPE

This report covers:

(a) The experimental procedure for irradiation and measurement of the pulse-height distributions of the unfractionated products of thermal-neutron fission of ^{235}U.

(b) The normalized and averaged experimental pulse-height distributions of the unfractionated products of thermal-neutron fission of ^{235}U taken at nine times (1/4, 1/2, 1, 2, 5, 10, 24, 48 and 72 hours) after fission.

(c) The gamma-ray spectra of the unfractionated products of thermal-neutron fission of ^{235}U for the nine selected times after fission.

(d) A comparison of the photon emission rate (photons/fission-sec) between the experimental and the computed gamma-ray spectra at 1, 2, 5, 24, 48 and 72 hours after fission.

(e) The spectral density histograms of the gamma-ray spectra of products of thermal-neutron fission of ^{235}U for the nine selected times after fission.

(f) A comparison of the spectral density histogram of the present experimental gamma-ray spectrum at 15 minutes with that of Maienschein et al at 16.67 minutes after fission.

(g) A comparison of the experimental photon emission rates from the products of thermal-neutron fission of ^{235}U with those of fast-neutron fission of ^{235}U.

SIGNIFICANT FINDINGS AND CONCLUSIONS

Experimental measurements of the gamma-ray spectra emitted by thermal-neutron-induced products of ^{235}U fission have been made at selected times (1/4, 1/2, 1, 2, 5, 10, 24, 48 and 72 hours) after fission. The experimental pulse-height distributions taken in a 1024-channel spectrometer were unfolded into 100-energy-bin gamma-ray spectra having an energy range of 0.065 to about 5.00 Mev.

A comparison of the photon emission rate (photons/fission-sec) is made between the present experimental gamma-ray spectra and the latest calculated spectra at 1, 2, 5, 24, 48 and 72 hours after fission. Plots of the spectral density, in units of (photons/fission-sec-Mev), of the photon emission rates are given for purposes of comparison of the experimental gamma-ray spectral data with other available data.

RECOMMENDATION

It is recommended that experimental measurements of the gamma-ray spectra of fractionated products of thermal-neutron fission of ^{235}U be performed, so that the effects of fractionation on gross-fission-product gamma-ray spectra may be measured. Such an experimental effort has been initiated in this laboratory.

Authors: L. R. Bunney, D. Sam

ABSTRACT

Experimental measurements of the gamma-ray spectra emitted by the products of thermal-neutron fission of ^{235}U have been made at nine selected times (1/4, 1/2, 1, 2, 5, 10, 24, 48 and 72 hours) after fission. A calibrated and highly collimated 5 in. x 5 in. NaI(Tl) detector was used.

The 100-energy-bin gamma-ray spectra were unfolded from the pulse-height distributions by means of an iterative method. Extensive use was made of machine computation. The number of fissions in each sample was determined radiochemically.

SUMMARY

Problem

The gamma-ray spectra of fission products resulting from nuclear weapon detonations provide fundamental input to fallout exposure and shielding calculations. This information is of considerable interest to the Office of Civil Defense and the military services in the preparation of practical plans for nuclear warfare defense.

This work presents experimental gamma-ray spectra of the unfractionated products of thermal-neutron fission of ^{235}U. The overall objective is to measure experimentally the effects of selected fission products on gross-fission-product gamma-ray spectra and to evaluate these effects on exposure rates calculated from gamma-ray spectra. The first phase of this project is to conduct experimental measurements of the gamma-ray spectra of the unfractionated products of thermal-neutron fission of ^{235}U. The second phase of this project is to conduct experimental measurements of the gamma-ray spectra of the fractionated products of thermal-neutron fission of ^{235}U. This report covers the first phase of this project.

Findings

Experimental measurements of the gamma-ray spectra emitted by thermal-neutron-induced products of ^{235}U fission have been made at selected times (1/4, 1/2, 1, 2, 5, 10, 24, 48 and 72 hours) after fission. The experimental pulse-height distributions were unfolded into 100-energy-bin gamma-ray spectra having an energy range of 0.065 to about 5.00 Mev.

A comparison of the photon emission rate (photons/fission-sec) is made between the present experimental gamma-ray spectra and the latest calculated spectra at 1, 2, 5, 24, 48 and 72 hours after fission. Plots of the spectral density, in units of (photons/fission-sec-Mev), are given for purposes of comparison of the experimental gamma-ray spectral data with other available data.

INTRODUCTION

The work described in this report was performed to provide direct experimental information on the gamma-ray spectra of the gross products of thermal-neutron fission of ^{235}U as a function of time after fission. In previous work[1,2] at this Laboratory the spectra from products of fast-neutron fission of ^{235}U and of ^{238}U were measured.

This spectral information has a number of uses, but it was sought here to improve the basis for the calculation of fallout exposure rates as a function of time after fission. While the thermal-neutron fission of ^{235}U does not precisely reproduce the radioactive composition of fallout, the products of such fission are the most extensively and accurately characterized of all fission processes and have thus been used frequently as an approximation of the products of a nuclear explosion (fast-neutron fission). Therefore, the differences between the thermal-neutron results and those for fast neutrons must be ascertained so that the accuracy of previous calculations of fallout characteristics based on thermal-neutron fission of ^{235}U may be better evaluated. In addition, experimental measurements of gamma-ray spectra of fractionated mixtures are feasible essentially only for thermal-neutron fission of ^{235}U. Consequently

determination of fractionation effects also requires data on the unfractionated products of thermal-neutron fission of ^{235}U.

Only two sets of experimental gamma-ray spectra[3,4] have been widely utilized, and only one[3] of these is for thermal-neutron fission of ^{235}U. The thermal-neutron studies extend for approximately 25 minutes after fission while the fast-neutron studies extend for only 45 seconds.

Several authors have synthesized gross-fission-product gamma-ray spectra from fission yields, half-lives and nuclear-decay-scheme information. Crocker and Turner[5] have most recently published such computed spectra. Their computations include 29 times after fission covering the period from 1 hour to 70 years. At times earlier than 1 hour, the decreasing quality of the necessary input data makes such computations quite uncertain. Earlier studies of both experimental and computed spectra have been reviewed by Keith and Shelton.[6]

EXPERIMENTAL

Gamma-ray pulse-height distributions were measured at nine selected times from 15 minutes to 3 days after fission. The widely used 1 hour post-fission point was included.

The main steps in the experimental procedure were: (1) assembly of the detector shield and pulse-height analyzer system, (2) calibration of the detector, (3) preparation of the samples, (4) irradiation of the samples, (5) measurement of the pulse-height distributions, (6) readout

of the data in a form suitable for machine computation, and (7) radio-chemical determination of the number of fission events in each sample. Steps (1), (2), (5), (6), and (7) were performed in a manner that was essentially identical with previous descriptions.[1,7]

Sample Preparation

The samples for the spectral measurements were pieces of uranium foil 0.038 mm thick and about 4 mm square, weighing approximately 10 mg each. The material utilized had been enriched to 93.2 % of the mass 235 isotope. Spectrographic analysis showed that the foil was 99.8 % pure uranium.

Packaging for irradiation and counting was designed to prevent the escape of any fission fragments from the samples while permitting subsequent radiochemical determination of ^{99}Mo. Each foil piece was wrapped in pure aluminum foil (for samples counted later than 1 hour after irradiation) or polyvinyl alcohol film (for samples counted at shorter times) and this packet was heat-sealed between two layers of 0.004 in. thick polyethylene film.

Irradiation and Counting of Samples

The samples were irradiated in a pneumatic rabbit facility of the Triga reactor of the Department of Nuclear Engineering of the University of California at Berkeley. This reactor can operate at power levels up to 1 Mw. At the maximum power level the slow (< 1 eV) neutron flux in the rabbit facility is approximately 10^{13} neutrons/cm^2-sec. The Cd ratio for Au is nearly 3.

In Table 1 are given the lengths of the irradiations, the reactor power level and the counting periods (relative to the midpoint of the irradiations) of the pulse-height measurements.

TABLE 1

Irradiation and Counting Times

Length of Irradiation (sec)	Reactor Power (kw)	Period of Count (After Midpoint of Irradiation) (min)
10	50	14 - 16
10	100	28 - 32
5	1000	57 - 63
8	1000	114 - 126
20	1000	285 - 315
40	1000	585 - 615
80	1000	1420 - 1460
		2835 - 2925
		4260 - 4380

The time intervals were measured with a stopwatch or electric clock. The durations of the irradiations were chosen to provide the best possible counting statistics without excessive dead time in the pulse-height analyzer and the attendant instrumental instability. In general, the relative dead time for the shorter counting intervals was about 20 %

and did not exceed 30 %. The actual amount of time available for measurement during each counting interval was obtained by a live timer gated by the analyzer. The counting intervals were chosen so as to give good counting statistics and to minimize decay effects.

Each sample as counted was fastened with tape to a thin sheet of polyethylene that was stretched over a polyethylene β-ray absorber. Reproducible geometry was obtained by placement of the sample in the center of a series of concentric rings drawn on the polyethylene absorber.

The pulse-height data were recorded in the ferrite core memory of a mobile analyzer which could be located at the reactor site for early-time measurements. The data were rapidly transferred to 1/4 in. wide magnetic tape for interim storage. The data on the tape were then read back into the memory of a similar pulse-height analyzer in the laboratory and punched out on cards through an IBM-523 Gang Summary Punch.[8] In this form the data were ready for entry into the computer.

Fission Determinations

Determination of the number of fission events produced in each sample was accomplished by radiochemical measurement of ^{99}Mo in each uranium sample and its associated wrapping. Previously determined calibration factors permitted conversion of the results of the ^{99}Mo analyses to the absolute number of fissions with an estimated error of about ± 10 %. This error is somewhat larger than previously estimated due to unforeseen difficulties that were experienced in this work.

DATA PROCESSING AND RESULTS

The basic experimental information obtained in this work consisted of the pulse-height distributions due to the gamma rays emitted by the products of slow-neutron fission of ^{235}U. These measurements were made in triplicate (or more) at nine selected time intervals after fission. The midpoints of the counting periods were 1/4, 1/2, 1, 2, 5, 10, 24, 48 and 72 hours after the midpoints of the irradiations. The irradiations were short compared to the time interval between fission and counting.

The necessary background correction was applied to the experimental data by subtraction of an experimentally measured background pulse-height distribution. These background measurements were always taken within 4 hours of the corresponding experimental measurement. By activation analysis, corrections due to activation of impurities in the samples and their wrappings were found to be negligible.

After background subtraction, the pulse-height distributions were normalized on the basis of the number of fissions measured radiochemically in each sample. This normalization (to net counts per second per fission per channel) permitted the comparison of replicate results. In general, the agreement was excellent. The average spread in the overall counting rates of the nine sets of replicates was 6.4 percent, with a maximum spread of 12.6 percent. Each set of pulse-height distributions was averaged on a channel-by-channel basis. Figure 1 shows the

normalized and averaged pulse-height distributions at the nine selected times after fission.

The average pulse-height distribution for each elapsed time was unfolded into the corresponding gamma-ray spectrum by an iteration technique, which was described by Hubbell and Scofield[9] and elaborated upon by Scofield.[10] Essential features of the necessary computer program are given by Smith and Scofield.[11] Their program required extensive modification to accommodate 1024-channel pulse-height distributions and gamma-ray spectra with 100 energy bins. These modifications and a complete listing of the computer programs used in the data processing have been reported previously.[7] Some minor modifications were made in the programs for this work to accommodate to the UNIVAC-1108 computer, which was used in place of the IBM-704 for the data processing.

The calibration of the spectrometer was the same as previously described.[1,7] The unfolding technique, as shown in earlier work,[1] places a very large portion of each component of a known mixture* of equally abundant gamma-rays in the correct energy bin and much smaller portions in the immediately adjacent bins. On the average, the unfolded photon-emission-rate results have been about 5 percent high compared to known inputs.

In Table 2 are listed the mid-bin energy and the width of each of the 100 energy bins. The results of the unfoldings are given in Tables

*Several mixtures were examined.

3 through 11 for the nine selected post-fission times. The data are presented in the E format of the computer printout (e.g. E-05 is read 10^{-5}).

DISCUSSION

A comparison of the number of photons per fission-second can be made between the present work and the latest calculated (thermal-neutron-produced) spectra[5] at 1, 2, 5, 24, 48 and 72 hours. Table 12 presents these data and the ratio of experimental to calculated results. This comparison shows a more rapid decay of the experimental photon emission rate than the calculated rate. It should be borne in mind that the experimental rate does not include photons below 60 keV, while the calculated rate does.

For comparison purposes, plots of the spectral density (the emission rate per MeV of energy-bin width plotted against the energy) are frequently employed. Such graphs are given in Figs. 2, 3 and 4 for the selected times after fission. This type of graph is chosen since by normalization it removes the effect of varying widths of energy bins for differing sources of information. We reiterate that these are not gamma-ray spectra, but normalized graphs that resemble but do not duplicate spectra. In Fig. 5, a comparison of two such graphs is made. Our results for 15 minutes post-fission are shown along with those of Maienschein et al.[3] for 16.67 minutes. As can be seen in the figure,

the agreement is good. In some regions significant differences occur such as that near 3.5 MeV. However, the most important overall difference is the slightly lower photon emission rate results obtained by us compared to the earlier work. This is of greater significance since the results for the earlier work are given at a slightly later time and hence would be expected to be slightly higher if the times coincided exactly.

The divergence in results above 4.5 MeV is thought to be due to our unfolding method, which gives somewhat high results in the highest few energy bins.

Table 13 shows a comparison of the experimental photon emission rates for products of thermal-neutron fission and fast-neutron fission of ^{235}U. The differences at the earlier times (up to about 2 hours post-fission) may be due to the combination of changes in chain yields and independent yields with neutron energy. At the later times, differences in independent yields should have a decreasing effect, and the variations should be due primarily to changes in the chain yields. Since the magnitude of the changes in chain yields of important fission products is small and fairly well measured, it is surprising to find the significant differences in photon emission rates shown in the table. Examination of the gamma-ray spectra due to the products of fission by the two neutron-energy distributions does not reveal any significant differences in spectral shape. Hence, the quantitative differences mentioned above appear to be spread throughout the energy spectra.

Experimental errors should not be sufficiently large to account for the spread in values, although they may contribute to it. Therefore the products of thermal-neutron fission of ^{235}U should be used as a simulant for unfractionated fallout material only in those cases where differences in photon emission rate of approximately $\pm$ 25 % are unimportant or where a correction can reasonably be applied.

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Table 2

Energy and Width of Energy Bins

Bin No.	Mid-bin Energy (MeV)	Width (MeV)	Bin No.	Mid-bin Energy (MeV)	Width (MeV)
1	0.07	0.01	51	1.470	0.05
2	0.08	0.01	52	1.520	0.05
3	0.09	0.01	53	1.570	0.05
4	0.10	0.01	54	1.620	0.05
5	0.11	0.01	55	1.670	0.05
6	0.12	0.01	56	1.720	0.05
7	0.13	0.01	57	1.770	0.05
8	0.14	0.01	58	1.820	0.05
9	0.15	0.01	59	1.870	0.05
10	0.16	0.01	60	1.925	0.06
11	0.17	0.01	61	1.985	0.06
12	0.18	0.01	62	2.045	0.06
13	0.19	0.01	63	2.105	0.06
14	0.20	0.01	64	2.165	0.06
15	0.215	0.02	65	2.225	0.06
16	0.235	0.02	66	2.285	0.06
17	0.255	0.02	67	2.345	0.06
18	0.275	0.02	68	2.405	0.06
19	0.295	0.02	69	2.465	0.06
20	0.315	0.02	70	2.525	0.06
21	0.335	0.02	71	2.585	0.06
22	0.355	0.02	72	2.645	0.06
23	0.375	0.02	73	2.705	0.06
24	0.395	0.02	74	2.770	0.07
25	0.420	0.03	75	2.840	0.07
26	0.450	0.03	76	2.910	0.07
27	0.480	0.03	77	2.980	0.07
28	0.510	0.03	78	3.050	0.07
29	0.540	0.03	79	3.120	0.07
30	0.570	0.03	80	3.190	0.07
31	0.600	0.03	81	3.265	0.08
32	0.630	0.03	82	3.345	0.08
33	0.665	0.04	83	3.425	0.08
34	0.705	0.04	84	3.505	0.08
35	0.745	0.04	85	3.585	0.08
36	0.785	0.04	86	3.665	0.08
37	0.825	0.04	87	3.750	0.09
38	0.865	0.04	88	3.840	0.09
39	0.905	0.04	89	3.930	0.09
40	0.945	0.04	90	4.020	0.09
41	0.985	0.04	91	4.115	0.10
42	1.025	0.04	92	4.215	0.10
43	1.070	0.05	93	4.315	0.10
44	1.120	0.05	94	4.415	0.10
45	1.170	0.05	95	4.515	0.10
46	1.220	0.05	96	4.615	0.10
47	1.270	0.05	97	4.715	0.10
48	1.320	0.05	98	4.820	0.11
49	1.370	0.05	99	4.930	0.11
50	1.420	0.05	100	5.040	0.11

TABLE 3

GAMMA-RAY SPECTRUM OF THE PRODUCTS OF THERMAL-NEUTRON FISSION OF URANIUM-235 AT 15 MINUTES AFTER FISSION

ENERGY BIN NO.	PHOTONS/ FISSION-SEC	ENERGY BIN NO.	PHOTONS/ FISSION-SEC
1	.1130-04	51	.8600-05
2	.8020-05	52	.6170-05
3	.9620-05	53	.5120-05
4	.6720-05	54	.4560-05
5	.3840-05	55	.5760-05
6	.2730-05	56	.7140-05
7	.3070-05	57	.6920-05
8	.5540-05	58	.4720-05
9	.4810-05	59	.3310-05
10	.5360-05	60	.4230-05
11	.9230-05	61	.7570-05
12	.1270-04	62	.7200-05
13	.9910-05	63	.3950-05
14	.9720-05	64	.5640-05
15	.9560-05	65	.7320-05
16	.1080-04	66	.3640-05
17	.2360-04	67	.2150-05
18	.9610-05	68	.2060-05
19	.3140-04	69	.2240-05
20	.2610-04	70	.3070-05
21	.9600-05	71	.3910-05
22	.1150-04	72	.3410-05
23	.5870-05	73	.2370-05
24	.8980-05	74	.1480-05
25	.1940-04	75	.1020-05
26	.2440-04	76	.7350-06
27	.1150-04	77	.6190-06
28	.8070-05	78	.6810-06
29	.7360-05	79	.7390-06
30	.1870-04	80	.7200-06
31	.1920-04	81	.7760-06
32	.1290-04	82	.7810-06
33	.1150-04	83	.6970-06
34	.1670-04	84	.7940-06
35	.1630-04	85	.8280-06
36	.1810-04	86	.5500-06
37	.1920-04	87	.3680-06
38	.2780-04	88	.3460-06
39	.3100-04	89	.3810-06
40	.2500-04	90	.4230-06
41	.1310-04	91	.3990-06
42	.2490-04	92	.3010-06
43	.1510-04	93	.2440-06
44	.1140-04	94	.2140-06
45	.1090-04	95	.1950-06
46	.1610-04	96	.1970-06
47	.1850-04	97	.2110-06
48	.8820-05	98	.2230-06
49	.1040-04	99	.2370-06
50	.1370-04	100	.2900-06

TOTAL .8051-03

TABLE 4

GAMMA-RAY SPECTRUM OF THE PRODUCTS OF THERMAL-NEUTRON FISSION OF URANIUM-235 AT 30 MINUTES AFTER FISSION

ENERGY BIN NO.	PHOTONS/ FISSION-SEC	ENERGY BIN NO.	PHOTONS/ FISSION-SEC
1	.3870-05	51	.7730-05
2	.4550-05	52	.3320-05
3	.4950-05	53	.2710-05
4	.3540-05	54	.2180-05
5	.2460-05	55	.2430-05
6	.1250-05	56	.3260-05
7	.1560-05	57	.3470-05
8	.3050-05	58	.2540-05
9	.3540-05	59	.1920-05
10	.3320-05	60	.1990-05
11	.3950-05	61	.3320-05
12	.5850-05	62	.3670-05
13	.6490-05	63	.1920-05
14	.5870-05	64	.2800-05
15	.5420-05	65	.4670-05
16	.3680-05	66	.2250-05
17	.1030-04	67	.1190-05
18	.7160-05	68	.1170-05
19	.1660-04	69	.1240-05
20	.1990-04	70	.1540-05
21	.4920-05	71	.2180-05
22	.5770-05	72	.2150-05
23	.3290-05	73	.1250-05
24	.4110-05	74	.5560-06
25	.8930-05	75	.3490-06
26	.1510-04	76	.3040-06
27	.8200-05	77	.3130-06
28	.3410-05	78	.3380-06
29	.6570-05	79	.3410-06
30	.7630-05	80	.3030-06
31	.6970-05	81	.2540-06
32	.8460-05	82	.2170-06
33	.8520-05	83	.2020-06
34	.4250-05	84	.2280-06
35	.9510-05	85	.2400-06
36	.9030-05	86	.1870-06
37	.6570-05	87	.1320-06
38	.1540-04	88	.1150-06
39	.1820-04	89	.1190-06
40	.1430-04	90	.1230-06
41	.6160-05	91	.1110-06
42	.1310-04	92	.9090-07
43	.8700-05	93	.7780-07
44	.4690-05	94	.7150-07
45	.5640-05	95	.6800-07
46	.7060-05	96	.6870-07
47	.9130-05	97	.7310-07
48	.3820-05	98	.7730-07
49	.5000-05	99	.8480-07
50	.1210-04	100	.1100-06
		TOTAL	.4279-03

TABLE 5

GAMMA-RAY SPECTRUM OF THE PRODUCTS OF THERMAL-NEUTRON FISSION
OF URANIUM-235 AT 1 HOUR AFTER FISSION

ENERGY BIN NO.	PHOTONS/ FISSION-SEC	ENERGY BIN NO.	PHOTONS/ FISSION-SEC
1	.2650-05	51	.4550-05
2	.1740-05	52	.1460-05
3	.2210-05	53	.1150-05
4	.1090-05	54	.9550-06
5	.6700-06	55	.9460-06
6	.4630-06	56	.1210-05
7	.1210-05	57	.1380-05
8	.2650-05	58	.1170-05
9	.2000-05	59	.9380-06
10	.1600-05	60	.8480-06
11	.2460-05	61	.1070-05
12	.2720-05	62	.1090-05
13	.2180-05	63	.7000-06
14	.2270-05	64	.1310-05
15	.1660-05	65	.2200-05
16	.1440-05	66	.9090-06
17	.3490-05	67	.6100-06
18	.3090-05	68	.8680-06
19	.9050-05	69	.8060-06
20	.5100-05	70	.8080-06
21	.1610-05	71	.1020-05
22	.1700-05	72	.9220-06
23	.1220-05	73	.4930-06
24	.2470-05	74	.2080-06
25	.4250-05	75	.1530-06
26	.8860-05	76	.1620-06
27	.2740-05	77	.1710-06
28	.1700-05	78	.1670-06
29	.4480-05	79	.1390-06
30	.2960-05	80	.1080-06
31	.1870-05	81	.9300-07
32	.5650-05	82	.8490-07
33	.3870-05	83	.7410-07
34	.1550-05	84	.6670-07
35	.6070-05	85	.6110-07
36	.3610-05	86	.5280-07
37	.4310-05	87	.4430-07
38	.1250-04	88	.4240-07
39	.8930-05	89	.4220-07
40	.4520-05	90	.3830-07
41	.2910-05	91	.3340-07
42	.5830-05	92	.2980-07
43	.2830-05	93	.2860-07
44	.2660-05	94	.2830-07
45	.2040-05	95	.2800-07
46	.2180-05	96	.2930-07
47	.2390-05	97	.3160-07
48	.1170-05	98	.3360-07
49	.2950-05	99	.3720-07
50	.9220-05	100	.4820-07
		TOTAL	.1982-03

TABLE 6

GAMMA-RAY SPECTRUM OF THE PRODUCTS OF THERMAL-NEUTRON FISSION OF URANIUM-235 AT 2 HOURS AFTER FISSION

ENERGY BIN NO.	PHOTONS/ FISSION-SEC	ENERGY BIN NO.	PHOTONS/ FISSION-SEC
1	.5890-06	51	.1710-05
2	.6270-06	52	.5610-06
3	.7960-06	53	.4100-06
4	.5960-06	54	.3720-06
5	.3910-06	55	.3920-06
6	.1850-06	56	.4590-06
7	.3150-06	57	.5670-06
8	.7300-06	58	.6670-06
9	.8950-06	59	.5480-06
10	.8910-06	60	.3260-06
11	.8210-06	61	.2740-06
12	.6790-06	62	.3280-06
13	.6430-06	63	.2690-06
14	.8780-06	64	.4360-06
15	.8530-06	65	.6810-06
16	.5560-06	66	.3320-06
17	.8170-06	67	.3290-06
18	.9460-06	68	.6540-06
19	.1260-05	69	.5000-06
20	.1150-05	70	.3420-06
21	.5930-06	71	.3770-06
22	.2910-06	72	.3240-06
23	.2700-06	73	.1770-06
24	.1040-05	74	.8150-07
25	.1530-05	75	.6390-07
26	.2460-05	76	.7410-07
27	.1420-05	77	.8540-07
28	.5050-06	78	.7850-07
29	.2170-05	79	.5490-07
30	.1440-05	80	.3970-07
31	.6540-06	81	.3410-07
32	.2520-05	82	.3090-07
33	.2700-05	83	.2660-07
34	.4720-06	84	.2350-07
35	.2630-05	85	.2130-07
36	.1800-05	86	.1920-07
37	.1670-05	87	.1630-07
38	.8530-05	88	.1460-07
39	.4400-05	89	.1370-07
40	.1600-05	90	.1230-07
41	.9820-06	91	.1130-07
42	.1820-05	92	.1050-07
43	.1480-05	93	.1010-07
44	.1400-05	94	.1010-07
45	.9490-06	95	.1010-07
46	.4710-06	96	.1070-07
47	.6410-06	97	.1170-07
48	.3990-06	98	.1270-07
49	.1640-05	99	.1420-07
50	.4090-05	100	.1870-07
		TOTAL	.7903-04

TABLE 7

GAMMA-RAY SPECTRUM OF THE PRODUCTS OF THERMAL-NEUTRON FISSION OF URANIUM-235 AT 5 HOURS AFTER FISSION

ENERGY BIN NO.	PHOTONS/ FISSION-SEC	ENERGY BIN NO.	PHOTONS/ FISSION-SEC
1	.1550-06	51	.9910-07
2	.9080-07	52	.1270-06
3	.2000-06	53	.1140-06
4	.1630-06	54	.8180-07
5	.1300-06	55	.1280-06
6	.5860-07	56	.1510-06
7	.8070-07	57	.1610-06
8	.1560-06	58	.2280-06
9	.2080-06	59	.1930-06
10	.2180-06	60	.7940-07
11	.1440-06	61	.5920-07
12	.1020-06	62	.8510-07
13	.1170-06	63	.7880-07
14	.1810-06	64	.1030-06
15	.1480-06	65	.1030-06
16	.3920-06	66	.5420-07
17	.5030-06	67	.1040-06
18	.1890-06	68	.2890-06
19	.2610-06	69	.1580-06
20	.1300-06	70	.6970-07
21	.8890-07	71	.5640-07
22	.7740-07	72	.4140-07
23	.6310-07	73	.2570-07
24	.1720-06	74	.1590-07
25	.3120-06	75	.1480-07
26	.1980-06	76	.1760-07
27	.1240-06	77	.1920-07
28	.2840-06	78	.1640-07
29	.1100-05	79	.1070-07
30	.4970-06	80	.7660-08
31	.8490-07	81	.6620-08
32	.5560-06	82	.5910-08
33	.1260-05	83	.5170-08
34	.1290-06	84	.4770-08
35	.9820-06	85	.4430-08
36	.4200-06	86	.3980-08
37	.3390-06	87	.3340-08
38	.1540-05	88	.2870-08
39	.7950-06	89	.2580-08
40	.4200-06	90	.2430-08
41	.1930-06	91	.2360-08
42	.4230-06	92	.2270-08
43	.3670-06	93	.2180-08
44	.4470-06	94	.2140-08
45	.2810-06	95	.2180-08
46	.1310-06	96	.2390-08
47	.3590-06	97	.2690-08
48	.8130-07	98	.2980-08
49	.8550-06	99	.3390-08
50	.9550-06	100	.4440-08
		TOTAL	.1992-04

TABLE 8

GAMMA-RAY SPECTRUM OF THE PRODUCTS OF THERMAL-NEUTRON FISSION OF URANIUM-235 AT 10 HOURS AFTER FISSION

ENERGY BIN NO.	PHOTONS/ FISSION-SEC	ENERGY BIN NO.	PHOTONS/ FISSION-SEC
1	.8310-07	51	.4750-07
2	.4170-07	52	.4000-07
3	.1090-06	53	.2720-07
4	.6290-07	54	.2200-07
5	.4510-07	55	.5000-07
6	.2950-07	56	.6690-07
7	.7060-07	57	.5520-07
8	.1170-06	58	.6680-07
9	.7420-07	59	.5510-07
10	.3880-07	60	.2290-07
11	.2700-07	61	.1510-07
12	.2890-07	62	.1750-07
13	.3070-07	63	.1670-07
14	.5530-07	64	.2080-07
15	.5760-07	65	.2300-07
16	.4390-06	66	.1550-07
17	.4340-06	67	.2430-07
18	.8530-07	68	.5990-07
19	.1660-06	69	.3710-07
20	.3630-07	70	.1090-07
21	.2720-07	71	.5700-08
22	.5330-07	72	.4980-08
23	.2450-07	73	.4480-08
24	.2050-07	74	.3370-08
25	.6380-07	75	.2940-08
26	.5470-07	76	.2950-08
27	.3250-07	77	.2620-08
28	.2260-06	78	.2070-08
29	.7380-06	79	.1600-08
30	.2290-06	80	.1330-08
31	.1960-07	81	.1190-08
32	.1320-06	82	.1050-08
33	.7420-06	83	.9220-09
34	.8000-07	84	.8570-09
35	.6320-06	85	.7980-09
36	.2500-06	86	.7540-09
37	.5800-07	87	.7060-09
38	.1310-06	88	.6670-09
39	.1150-06	89	.6410-09
40	.1770-06	90	.6270-09
41	.6780-07	91	.6290-09
42	.2130-06	92	.6380-09
43	.1220-06	93	.6510-09
44	.1560-06	94	.6690-09
45	.1300-06	95	.7060-09
46	.3880-07	96	.7890-09
47	.2140-06	97	.9100-09
48	.4790-07	98	.1030-08
49	.2050-06	99	.1180-08
50	.2940-06	100	.1540-08
		TOTAL	.8070-05

TABLE 9

GAMMA-RAY SPECTRUM OF THE PRODUCTS OF THERMAL-NEUTRON FISSION OF URANIUM-235 AT 1 DAY AFTER FISSION

ENERGY BIN NO.	PHOTONS/ FISSION-SEC	ENERGY BIN NO.	PHOTONS/ FISSION-SEC
1	.5210-07	51	.1350-07
2	.3910-07	52	.7010-08
3	.6550-07	53	.8240-08
4	.2760-07	54	.1300-07
5	.2040-07	55	.1580-07
6	.3460-07	56	.1480-07
7	.9610-07	57	.1210-07
8	.5520-07	58	.8490-08
9	.1500-07	59	.5540-08
10	.9530-08	60	.4090-08
11	.1120-07	61	.3100-08
12	.7870-08	62	.2350-08
13	.4750-08	63	.1900-08
14	.1600-07	64	.1740-08
15	.8240-07	65	.1650-08
16	.3800-06	66	.1470-08
17	.1930-06	67	.1430-08
18	.6250-07	68	.1400-08
19	.8790-07	69	.1090-08
20	.9570-08	70	.7610-09
21	.2280-07	71	.5740-09
22	.3690-07	72	.4810-09
23	.8030-08	73	.4140-09
24	.5930-08	74	.3540-09
25	.1510-07	75	.3430-09
26	.1290-07	76	.3180-09
27	.1110-07	77	.2900-09
28	.2210-06	78	.2630-09
29	.3400-06	79	.2440-09
30	.2490-07	80	.2310-09
31	.3870-08	81	.2230-09
32	.1480-06	82	.2150-09
33	.3980-06	83	.2060-09
34	.3880-07	84	.2020-09
35	.3970-06	85	.1980-09
36	.8730-07	86	.1980-09
37	.1830-07	87	.1990-09
38	.3020-07	88	.2030-09
39	.2950-07	89	.2070-09
40	.2830-07	90	.2130-09
41	.2950-07	91	.2200-09
42	.7880-07	92	.2270-09
43	.2740-07	93	.2360-09
44	.4730-07	94	.2460-09
45	.2510-07	95	.2620-09
46	.1940-07	96	.2920-09
47	.5730-07	97	.3330-09
48	.1420-07	98	.3740-09
49	.1550-07	99	.4290-09
50	.2600-07	100	.5340-09
		TOTAL	.3617-05

TABLE 10

GAMMA-RAY SPECTRUM OF THE PRODUCTS OF THERMAL-NEUTRON FISSION OF URANIUM-235 AT 2 DAYS AFTER FISSION

ENERGY BIN NO.	PHOTONS/ FISSION-SEC
1	.4410-07
2	.2910-07
3	.3480-07
4	.1290-07
5	.1100-07
6	.3640-07
7	.8790-07
8	.2560-07
9	.4870-08
10	.5140-08
11	.8050-08
12	.3790-08
13	.2120-08
14	.8790-08
15	.7060-07
16	.1160-06
17	.3510-07
18	.4740-07
19	.4610-07
20	.5320-08
21	.1520-07
22	.2690-07
23	.4800-08
24	.1830-08
25	.3950-08
26	.8020-08
27	.8060-08
28	.1110-06
29	.1180-06
30	.1670-08
31	.1000-08
32	.4730-07
33	.2060-06
34	.1920-07
35	.1590-06
36	.7920-07
37	.4670-08
38	.1410-07
39	.9820-08
40	.1130-07
41	.1150-07
42	.1290-07
43	.7260-08
44	.7650-08
45	.8110-08
46	.3740-08
47	.8450-08
48	.6560-08
49	.5790-08
50	.6550-08
51	.2220-08
52	.1570-08
53	.8570-08
54	.1920-07
55	.4340-08
56	.1400-08
57	.1210-08
58	.1190-08
59	.1170-08
60	.1260-08
61	.1080-08
62	.7850-09
63	.5940-09
64	.4730-09
65	.4190-09
66	.3790-09
67	.3410-09
68	.3190-09
69	.3050-09
70	.2820-09
71	.2300-09
72	.1760-09
73	.1400-09
74	.1170-09
75	.1150-09
76	.1090-09
77	.1050-09
78	.1000-09
79	.9540-10
80	.9100-10
81	.8980-10
82	.8650-10
83	.8410-10
84	.8410-10
85	.8390-10
86	.8520-10
87	.8680-10
88	.8880-10
89	.9150-10
90	.9490-10
91	.9820-10
92	.1010-09
93	.1050-09
94	.1100-09
95	.1150-09
96	.1270-09
97	.1420-09
98	.1590-09
99	.1800-09
100	.2180-09

TOTAL .1615-05

TABLE 11

GAMMA-RAY SPECTRUM OF THE PRODUCTS OF THERMAL-NEUTRON FISSION OF URANIUM-235 AT 3 DAYS AFTER FISSION

ENERGY BIN NO.	PHOTONS/ FISSION-SEC	ENERGY BIN NO.	PHOTONS/ FISSION-SEC
1	.3830-07	51	.7260-09
2	.2030-07	52	.7720-09
3	.2140-07	53	.1300-07
4	.7110-08	54	.2130-07
5	.6240-08	55	.1510-08
6	.3500-07	56	.3570-09
7	.6770-07	57	.3720-09
8	.1130-07	58	.4690-09
9	.2380-08	59	.5970-09
10	.4120-08	60	.7180-09
11	.4990-08	61	.6180-09
12	.1740-08	62	.4590-09
13	.1400-08	63	.3440-09
14	.8320-08	64	.2580-09
15	.5690-07	65	.2300-09
16	.3030-07	66	.2200-09
17	.4720-08	67	.2150-09
18	.3400-07	68	.2140-09
19	.2370-07	69	.2260-09
20	.4490-08	70	.2310-09
21	.1320-07	71	.1800-09
22	.1990-07	72	.1220-09
23	.2740-08	73	.9140-10
24	.1200-08	74	.7780-10
25	.2490-08	75	.7750-10
26	.6310-08	76	.7440-10
27	.1410-07	77	.7280-10
28	.6690-07	78	.7000-10
29	.3980-07	79	.6510-10
30	.1580-09	80	.6060-10
31	.1890-09	81	.5880-10
32	.3280-07	82	.5750-10
33	.1090-06	83	.5600-10
34	.1090-07	84	.5580-10
35	.8330-07	85	.5570-10
36	.4950-07	86	.5660-10
37	.4870-08	87	.5760-10
38	.8070-08	88	.5890-10
39	.5470-08	89	.6040-10
40	.1010-07	90	.6280-10
41	.5930-08	91	.6520-10
42	.2250-08	92	.6670-10
43	.1910-08	93	.6880-10
44	.4200-08	94	.7160-10
45	.3550-08	95	.7570-10
46	.1640-08	96	.8330-10
47	.2930-08	97	.9330-10
48	.3210-08	98	.1030-09
49	.4440-08	99	.1150-09
50	.3780-08	100	.1350-09
		TOTAL	.9444-06

TABLE 12

Comparison of Experimental and Calculated Photon Emission Rates

Time After Fission (hr)	Experimental Photons/Fission-sec	Calculated Photons/Fission-sec	$\frac{\text{Experimental}}{\text{Calculated}}$
1	1.98×10^{-4}	1.39×10^{-4}	1.42
2	7.90×10^{-5}	6.08×10^{-5}	1.30
5	1.99×10^{-5}	1.87×10^{-5}	1.06
24	3.62×10^{-6}	3.82×10^{-6}	0.95
48	1.62×10^{-6}	1.81×10^{-6}	0.90
72	9.44×10^{-7}	1.17×10^{-6}	0.81

TABLE 13

Comparison of Photon Emission Rates From Products of Fission of ^{235}U by Thermal Neutrons and Fast Neutrons

Time After Fission (hr)	Photons/Fission-sec From Products of Fission by (1) Thermal Neutrons	(2) Fast Neutrons[a]	Ratio, (2):(1)
0.25	8.05×10^{-4}	9.08×10^{-4}	1.13
0.5	4.29×10^{-4}	4.83×10^{-4}	1.13
1	1.98×10^{-4}	1.95×10^{-4}	0.98
2	7.90×10^{-5}	6.68×10^{-5}	0.85
5	1.99×10^{-5}	2.41×10^{-5}	1.21
10	8.07×10^{-6}	1.07×10^{-5}	1.33
24	3.62×10^{-6}	4.52×10^{-5}	1.25
48	1.62×10^{-6}	1.89×10^{-6}	1.17
72	9.44×10^{-7}	1.21×10^{-6}	1.28

a. These values were taken from Reference 1.

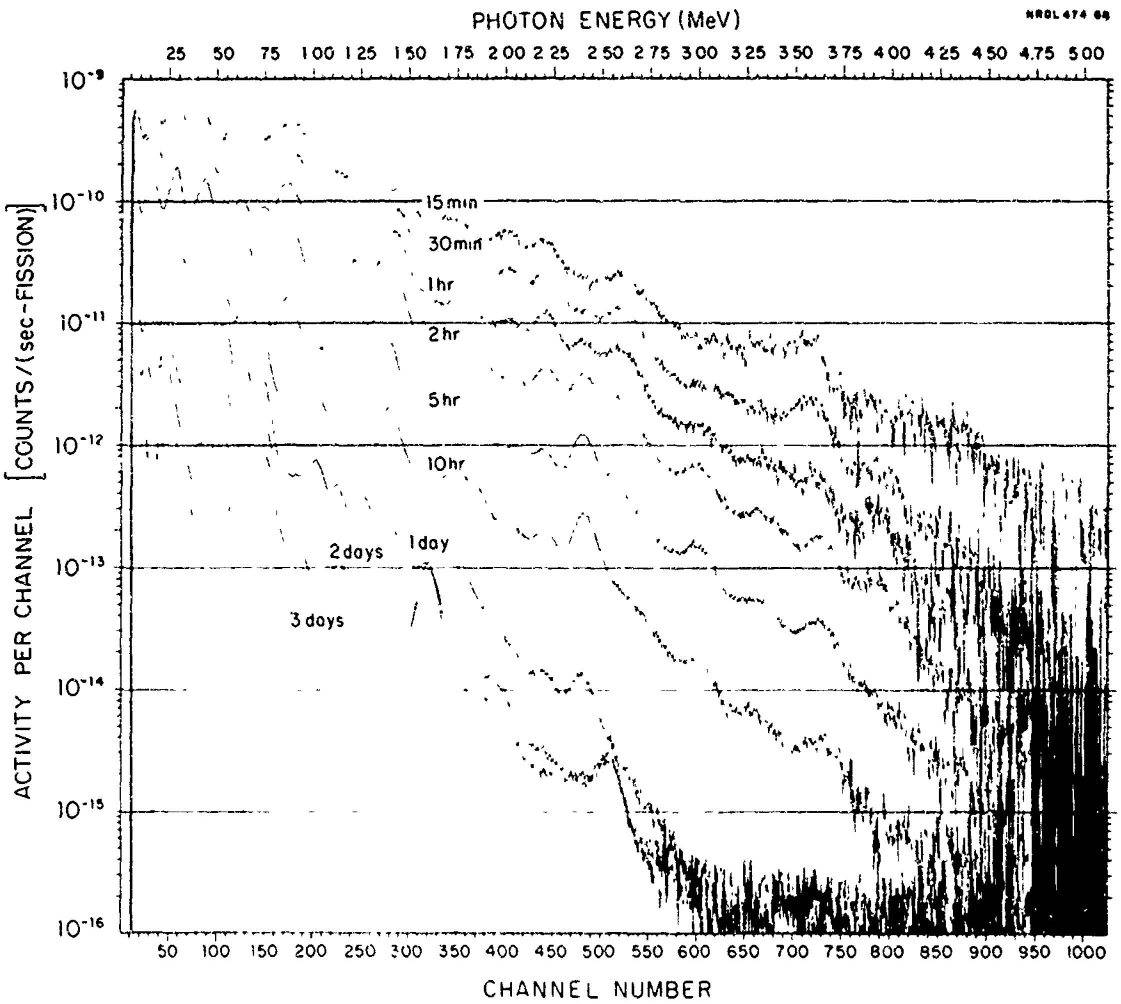

Fig. 1 Pulse-Height Distributions of Products of Thermal-Neutron Fission of ^{235}U at Selected Times After Fission.

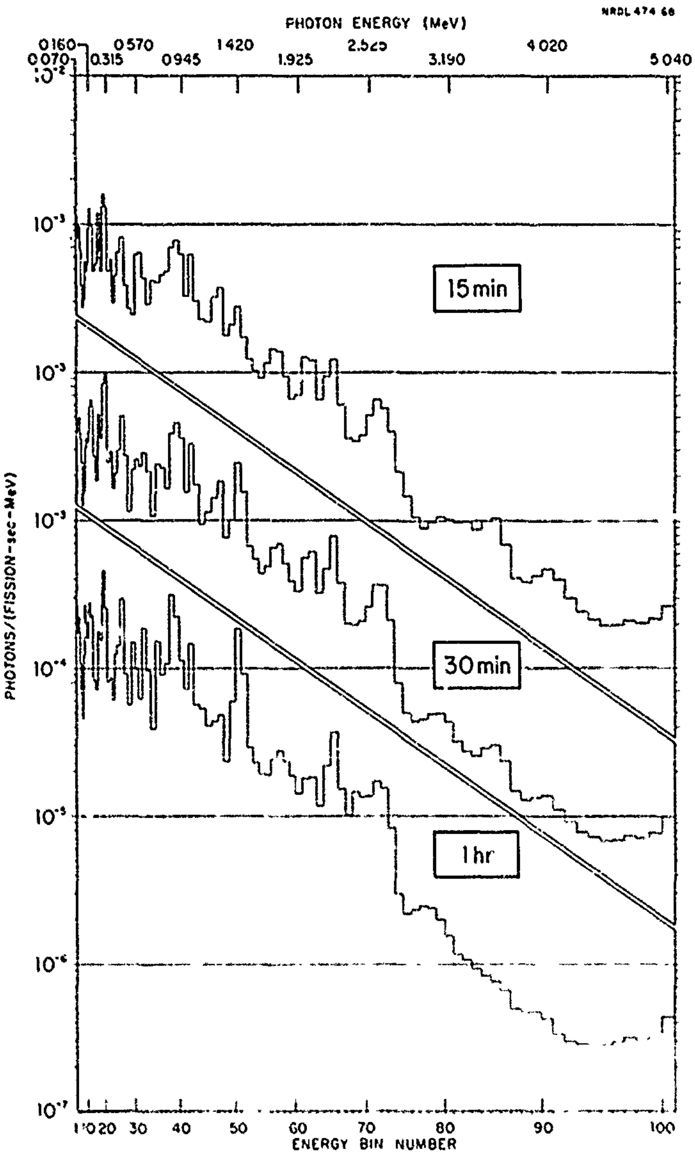

Fig. 2 Gamma-Ray Spectral-Density Histograms From Products of Thermal-Neutron-Fission of ^{235}U at Selected Times After Fission.

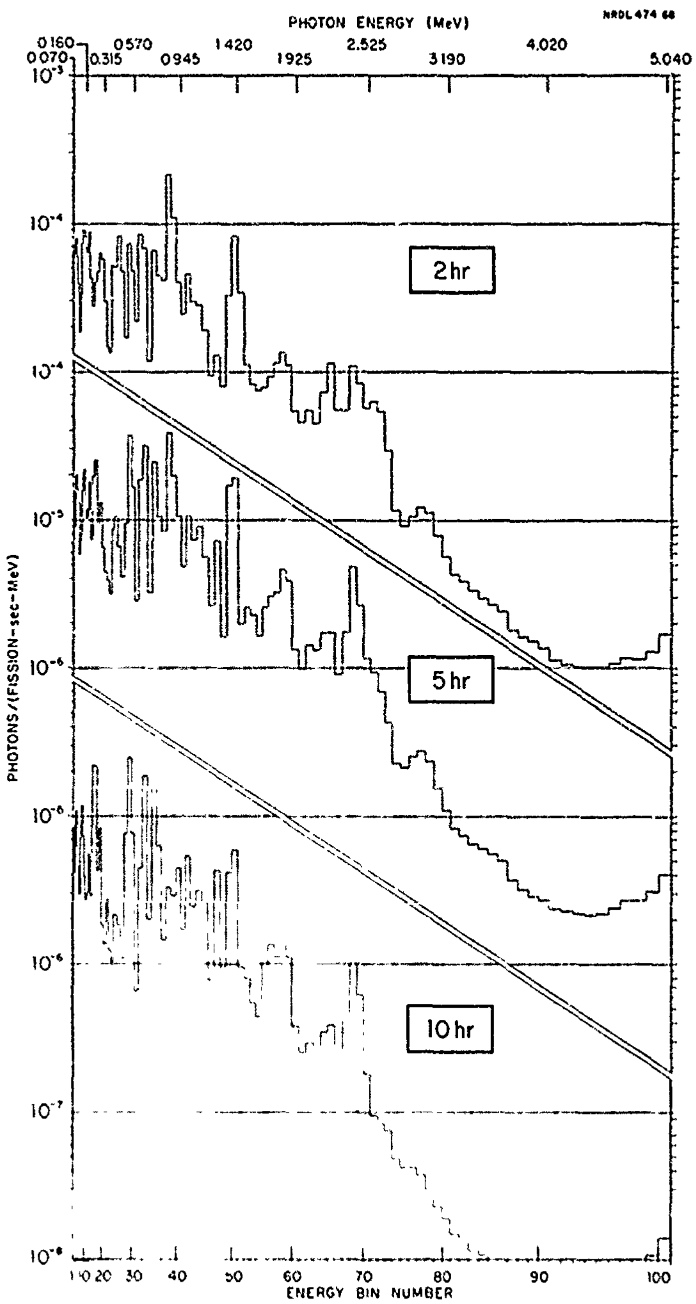

Fig. 3 Gamma-Ray Spectral-Density Histograms From Products of Thermal-Neutron-Fission of ^{235}U at Selected Times After Fission.

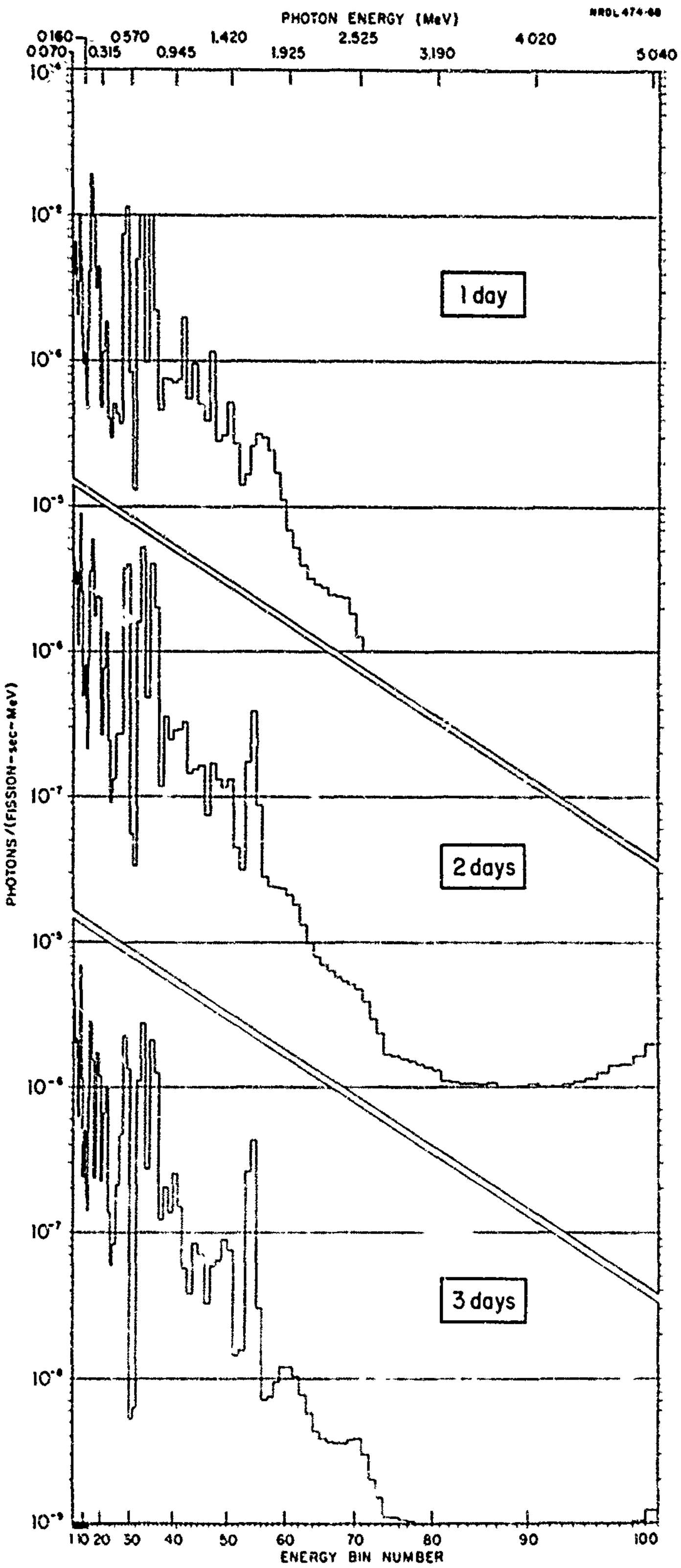

Fig. 4 Gamma-Ray Spectral-Density Histograms From Products of Thermal-Neutron Fission of ^{235}U at Selected Times After Fission.

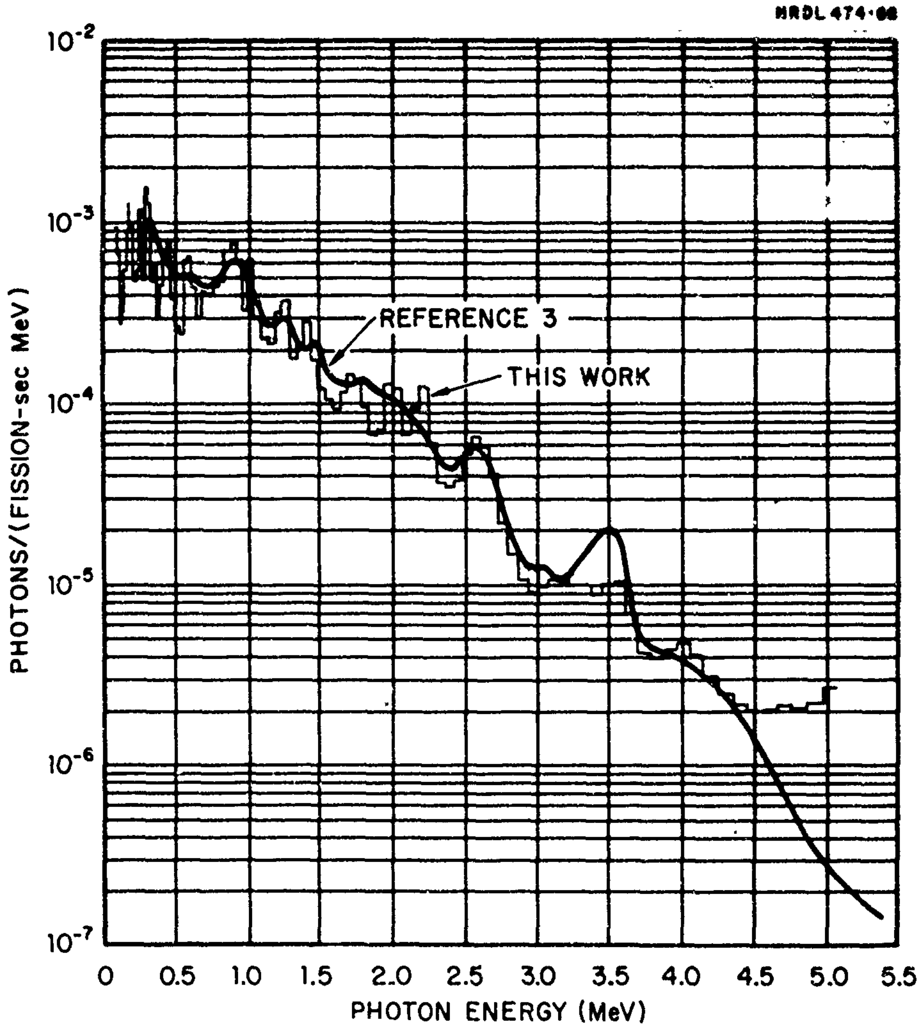

Fig. 5 Comparison of Experimental Gamma-Ray Spectral Densities.

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13. ABSTRACT

Experimental measurements of the gamma-ray spectra emitted by the products of thermal-neutron fission of ^{235}U have been made at nine selected times (1/4, 1/2, 1, 2, 5, 10, 24, 48, and 72 hours) after fission. A calibrated and highly collimated 5 in. x 5 in. NaI(Tl) detector was used.

The 100-energy-bin gamma-ray spectra were unfolded from the pulse-height distirubtions by means of an iterative method. Extensive use was made of machine computation. The number of fissions in each sample was determined radiochemically.

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